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The Impact of Activity Sequencing on Reducing Variability

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Abstract

Variation in production is deemed a major reason behind producing waste in onsite construction operations, resulting in a workflow that's full of delays and interruptions. To reduce the negative impact of waste in construction, production managers need to address the causes of variation that's resulting in such waste. This paper explains the way to reduce the effects of variation in construction by changing the tasks' sequence arrangement. The study analyzes the effect of some different tasks' sequence arrangements on each of the production gap, crew waiting time, and production delay by simulating a group of work tasks and changing the task sequence arrangement from linear to parallel. Accordingly, one hundred work activities have been simulated in 98 different sequence designs, using a stochastic discrete-event simulation model, during which the number of parallel activities are systematically increased. The main finding from the studied configuration is that; arranging tasks in parallel increases waste, while it reduces project duration. Moreover, waste resulting from variation is found to be an additional cause for waste when accelerating the production. Finally, it was revealed that the impact of variation on the tasks' sequence highly depends on how often the schedule is updated. This study helps production managers to better understand of how the tasks' sequence arrangement affects production performance in onsite construction operations.

Introduction

It is well known that productivity rates during on-site construction vary according to numerous reasons. Variation in task durations, especially when it is large, makes it difficult to predict the production outcome, and thus difficult to schedule production and maintain a steady flow. Positive variation occurs when the production output is high, while negative variation is when production output is low. Therefore, negative variations induce delays; while positive variations result in considerable gaps in the production workflow (Lindhard 2014a). In order to avoid work inactivity and generated wastes, these gaps need to be reduced (Lindhard 2014a).

The effect of variation in a task duration passes into the subsequent tasks in construction, where unpredictability increases as the number of work tasks increases (Wambeke, Hsiang et al. 2011). This makes the construction process very hard to manage (Hughes, Tippett et al. 2004), therefore; wasted time increases and labor productivity drops down (González, Alarcón et al. 2010; Thomas, Horman et al. 2002). To address this variation, two main strategies can be employed: 1) causes of variation are to be eliminated, and/or 2) effects of variation are to be reduced. First, the schedule's quality plays a vital role in inducing variations. If

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it is well planned, variations can be controlled to minimum. This entails ensuring that work sequence is well-established, required resources are available, constraints are removed, and estimated durations are realistic (Ballard, Howell 1998). Second, the effects of variation can be reduced by increasing the production flexibility. Maintaining adjustable crew sizes and work hours is one approach to ensuring that the production is on-schedule (Thomas, Horman et al. 2003). Another approach is shielding the production workflow with buffers. Buffers are divided into different categories such as time, capacity, or inventories (Hopp and Spearman 2000). Time buffers are represented as extra time embedded in the schedule to absorb the effects of delays and ensure the on-time project completion (Park, Peña-Mora 2004). On the other hand, capacity buffers include extra capacity of labor and equipment which absorb variation in demands (González et al. 2009). Inventory buffers include buffers of raw materials and work in process. All buffers are used to shield the production and ensure a smooth production (González et al. 2011; Lindhard, Wandahl 2014). Despite the existing related research, variation in durations is still considered a problem in construction. Accordingly, new approaches and tools are required to dampen the effects of variation. This study takes different approach, where the effects of variation is reduced by changing the task sequence arrangement.

Background

The prediction of the production progress is sometimes problematic in on-site construction (Russel et al. 2004). The unpredictability of task duration is caused by varying labor productivity, uncertainty in quality of estimates, and the possibility of changes during construction (Hanif et al. 2016; Russel et al. 2014; González et al. 2010). Howick (2003) and Flyvberg et al. (2009) have underlined that uncertainty in estimates have a huge impact on time-, cost-, and quality performance. Despite the effort to improve production estimates, some uncertainties and concomitant variation in task duration still exist; this is due to variation in labor productivity (Arashpour, Mehrdad 2015).

In Lean Construction, seven pre-conditions are required to carry out the work including prerequisite work, material, labor, equipment, tools, space, and external conditions such as weather (Koskela 1999). Besides these pre-conditions, there is a set of influencing factors of the productivity such as quality of the equipment, design material, supervision, work method, weather, work organization, and competency of workforce. (Thomas et al. 1986; Thomas et al. 1987; Tsehayae, Fayek 2015). But even within a fixed productivity base-line, labor productivity is bound to vary (Arashpour, Mehrdad 2015).

Variation in labor productivity is understood as the difference from production mean, where productivity is understood as units of work per work hour (output/work hour) (Thomas et al. 1990; Thomas, Sakarcan 1994). Variation induced waste which is understood as wasted time due to work inactivity (Alarcón 1997). On the other hand, the periods of inactivity are defined as gaps in the production. Gaps, induced by both positive and negative variations, in production have an unexploited potential. In addition to the gaps, variation causes delay, which in return leads to interruptions and delays in the workflow (Lindhard 2014b). In order to reduce the negative effects of variation on labor productivity and performance, its causes and nature need to be analyzed. The contribution of this paper is to how the task sequence arrangement can affect the impact of variation, and thus how the sequencing of activities can be used as an instrument to reduce gaps, delay and waiting time.

It is important to state that changing the schedule only should be done after carefully having considered the impacts. Changing the schedule and especially the near term can become costly due to the concomitant confusion and changes and it creates in the need for materials, workers etc. (Metters, Vargas 1999; Krajewski et al. 2005).

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Research Focus

Variation in labor productivity have a negative impact on performance. Several research studies have looked into removing or reducing these effects (Thomas, Horman et al. 2002; Ballard, Howell 1998). Improved schedule quality is one approach to remove variation, and thus improve performance (González, Alarcón et al. 2010; Howick 2003). Improved schedule quality can be achieved by ensuring that the scheduled activities are made-ready, and improving the production estimates (Ballard, Howell 1998; Hamzeh et al. 2015).

Increasing production flexibility reduces the effects of variation. Traditionally, flexibility in the production is gained using buffers or through maintaining adjustable work hours. This study takes a novel approach, where the task sequence is rearranged to make the schedule as robust against variation as possible.

The ideal approach would be a combination of ’removing and reducing’, where the effects of the variation slipping through to the production is managed and reduced (Wambeke, Liu et al. 2012, González, Alarcón et al. 2011, Khamooshi, Cioffi 2009).

In addition to previous approaches, Lindhard (2014b) have looked into schedule robustness by simulating variation in two different sequence patterns. It has been found that the design of the task sequence has a significant effect on how variation emerges during production and how it affects the schedule. Moreover, the study has shown that variation in labor productivity is only creating waste between handovers; thus, by clustering work tasks and reducing handovers the overall production waste is reduced.

The fact that the design of the sequence impacts the effects of variation is important, especially when production managers tend to compress the schedule to make up for lost time without knowing how the compression could shape the effects of variation. Therefore, in order to increase the level of understanding of the effects of a compressed schedule, this study attempts to answer the following research question: *How does the use of parallel activities in task sequence affect schedule robustness and wasted production time?*

The effect of compressing the schedule is shown by simulating first a liner sequence of activities and then gradually changing the sequence into parallel activities. The results of 98 different sequence arrangements corresponding to 98 different ways to schedule the project are examined in this study. In each simulation, the sequence arrangement is kept fixed and independent. The simulation is an intellectual experiment where the purpose is to identify how the arrangement of the tasks impacts the effects of variation. In the simulation value creation, the flow of pre-requisites and resources are considered as given, thus; the simulation is mainly focused on the transformations.

Despite numerous of studies which have looked into how variation in labor productivity can be handled, none has focused on using the schedule itself to reduce the effects. This study looks from a theoretical point of view into how the sequence can be rearranged in order to reduce the negative effects of variation. The study’s results are helpful to production managers when determining the best task sequence for a project or when trying to compress the schedule to finish the project on time. The findings will give project managers and planners knowledge on best practices to reduce variation in a schedule and shield a schedule from the negative effects of unavoidable variation.

Research Methods

The interdependence and sequence of activities hugely impact production workflow (Lindhard 2014b). In a sequence of activities, the completion of previous activities is a necessity before the following activity can

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start. In construction, variation in labor productivity creates complexity and waste resulting in reduced productivity (Lee et al. 2011; González et al. 2009). To understand how the effect of variation in productivity can be handled, a simulation study is carried out. The focus of the simulation is to show how variation affects the production output, and how changes in the sequence have the potential to change the magnitude of these effects.

The simulation study is based on the simulation design presented in Lindhard (2014b). It uses a stochastic discrete-event simulation model created in excel. The simulation model is used to calculate labor productivity so that the throughput of each task can be calculated together with the gaps and delays which depend on the sequence. Lindhard (2014b) has focused on how the duration of activities affected the production. In this study, the focus is on the sequence and the effect of parallel activities.

Labor production is simulated using a beta distribution as suggested by AbouRizk and Halpin (1992). The shape of the distribution depends on the nature of the task. In the simulation, the shape parameters α and β is set to 1.898 and 6.372. The shape parameters are derived from Fente et al. (2000), who studied the shape parameters to a truck haul. By setting $\alpha < \beta$, the distribution becomes right skewed with the mean and median placed in the right side of the range (Fente et al. 2000). If production estimates of the task duration take outset in production mean, the risk of delayed activities equals the likelihood of activities completing ahead of schedule. The equilibrium between the likelihood of positive and negative variation is only preserved if the basis and assumptions are not changed. Thus, incorrect estimates of task duration as well as changing manning or work hours affect the amount of positive and negative delay. For example, Khamooshi (2009) and Khamooshi (2012) found that activities are almost never completed ahead of schedule; this is because of optimistic estimates of duration or changes in manning (Khamooshi, Cioffi 2012). This aligns with what Khamooshi and Cioffi (2012) observed and defined as the “student syndrome”. The “student syndrome” is when the work is postponed until the very end of task duration, which increases the risk of delay.

As in Lindhard (2014), the productivity of each subcontractor is calculated by a discrete stochastic variable, taking integers (1; 2; 3; 4; 5; and 6) following a beta distribution. The production mean is 1.88 and set as the target output, while the duration to every activity is set to a workweek equivalent to six work days, thus 11 production units is required in order to complete each activity. Furthermore, when completing an activity, the started work day is included as a whole; thus, any remaining production capacity that was not used at the end of the day is regarded as waste. The production output is analyzed by calculating the following measurements:

- Network Gap: is the gap/(s) in the production caused by the interdependencies in the network of activities. The gap emerges when parallel activities are not completed simultaneously because the start of a subsequent activity needs to wait until all previous activities are completed.
- Variation Gap: is the gap/(s) in the production caused by positive variation. It happens when an activity is completed ahead of schedule, and the subsequent activity is not yet ready.
- Waiting days$_{nup}$: is the number of waiting days caused by delayed activities. Waiting days$_{nup}$ is based on a situation where the initial schedule is not updated; thus, the initial schedule is followed regardless of the delays in previous activities.
- Waiting days$_{up}$: is waiting caused by delays in the system. Waiting days$_{up}$ is based on a situation where the schedule is updated after each completed activity; thus, the schedule is updated after the completion of each activities to track the current progress.

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- Delay$_{nup}$: is delay caused by both positive and negative variations. However, positive variation cannot bring the production ahead of schedule because the following activity will always start on schedule.
- Delay$_{up}$: includes only negative variation, and it is a measurement of the delay emerging if the schedule is updated after each completed activity. Therefore, the start time of the following activity is continuously adjusted.

The simulation experiment consists of 100 interdependent activities. These activities are arranged in 98 different sequences, where each one is simulated 100 times to strengthen the research validity and consistency, as per Krefting (1991), and average values are used.

During each simulation run, the number of parallel activities are increased by one starting from a linier sequence and ending with a simulation where 98 of the activities are parallel. The parallel activities are placed after the first activity so that the effects before and after the parallel activities can be simulated. Thus, in the first simulation-run, all activities are arranged in a linear sequence as shown in Fig. 1A. In the second simulation-run 1 activity is completed followed by 2 parallel activities and ending with 97 linear activities. In the third simulation-run 1 activity is completed followed by 3 parallel activities and ending with 96 linear activities. The number of parallel activities continues to increase by one until the final and 98th simulation-run, where 1 activity is completed followed by 98 parallel activities and ending with 1 linear activities, as shown in Fig 1B.

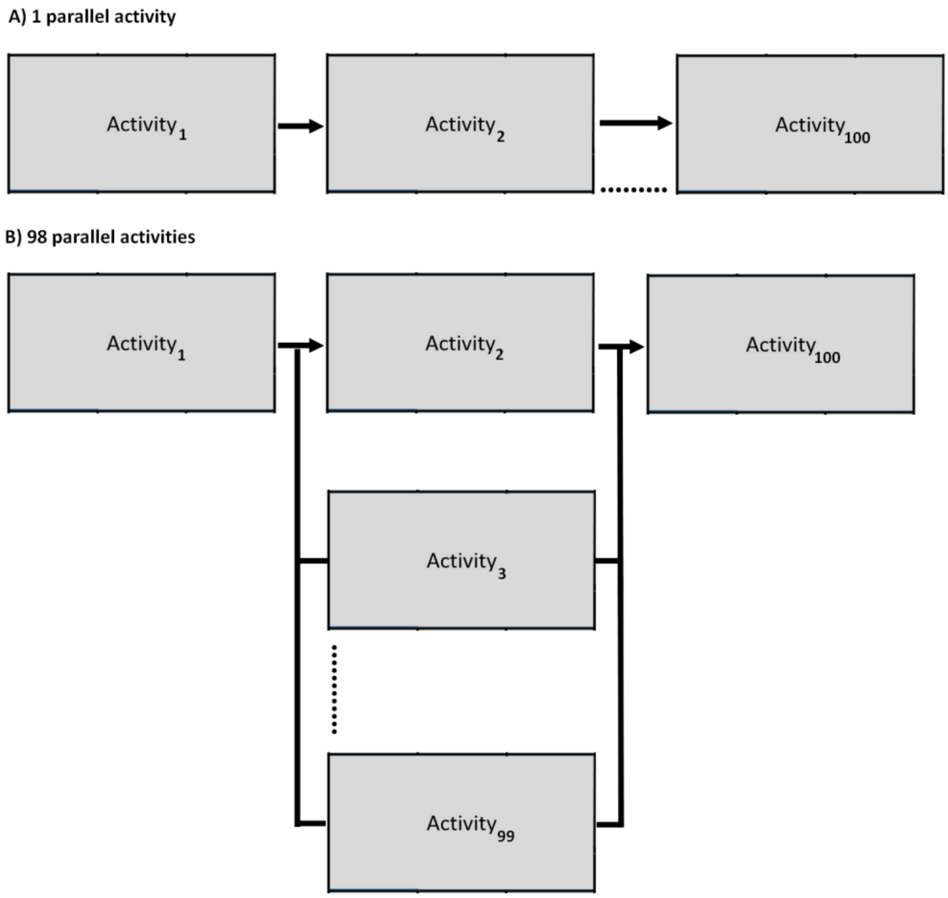

Fig. 1: The sequence extremes; A) a linier sequence; B) 98 parallel activities

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When analyzing the data, the previously defined measurements are calculated for each activity. These measurements, as stipulated in Fig. 2, are presented in the results section.

Fig. 2: *Model used for analyzing and presenting the simulated data.*

Results and Discussion

Variation creates interruptions in the production work flow and decreases productivity (González, Alarcón et al. 2010). In order to reduce the negative effect of variation, it needs to be understood. The design of the activity sequence has a huge impact on how variation influences the production workflow.

When looking into the effect of parallel activities, the focus is on changes in the sequence from linear to parallel. As the only change to the sequence is the gradual increase in parallel activities, the effect on schedule emerges from this change. Thus, focus needs to be on the time between the overlap with the just completed activity before the parallel activities and the overlap with the following activity. Moreover, because the effects of each change are carried down the sequence, the effects on the entire production system are also important. A summation of the simulation results is shown in Fig. 3, where the results from three scenarios having 1, 2, and 3 parallel activities is shown. The following sections present an in-depth analysis of the different parameters measured.

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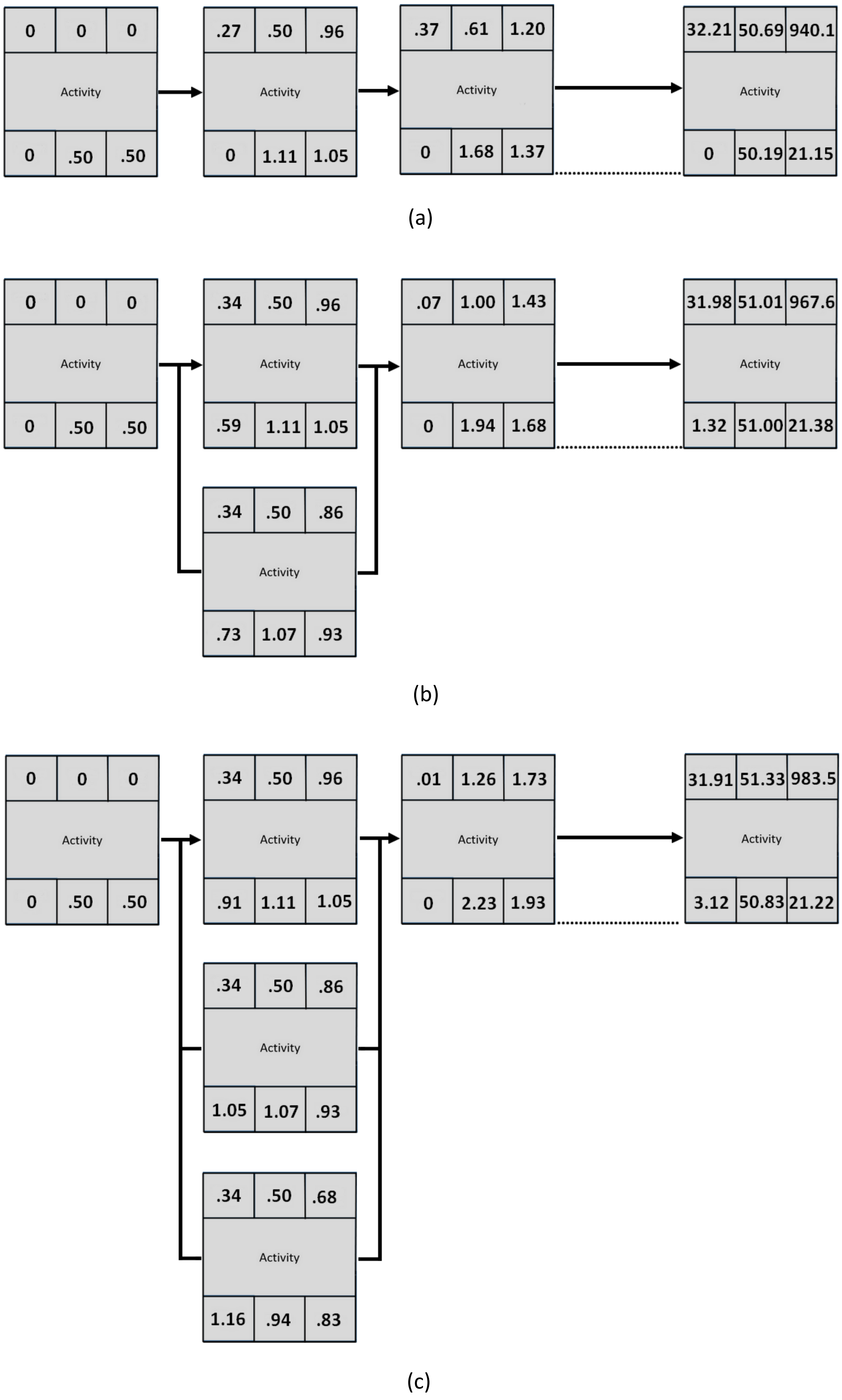

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201 ***Fig.3:*** *Simulation results for three scenarios having (a) one, (b) two, and (c) three parallel activities.*

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Gaps in production

The summation of gaps in production is equivalent to the production time wasted. Positive variation creates unexploited gaps in production, where an activity which was completed early leaves a time-gap before the subsequent activity starts. These gaps are defined as Variation Gaps.

When increasing the number of parallel activities, the Variation Gap created by the parallel activities approaches zero as shown in Fig. 4. The reduction in the Variation Gap when increasing the number of parallel activities is caused by a decreasing likelihood for all activities to be completed ahead of schedule. Consequently, it can be derived that the size and the speed by which the Variation Gap approaches zero depends on variation in production.

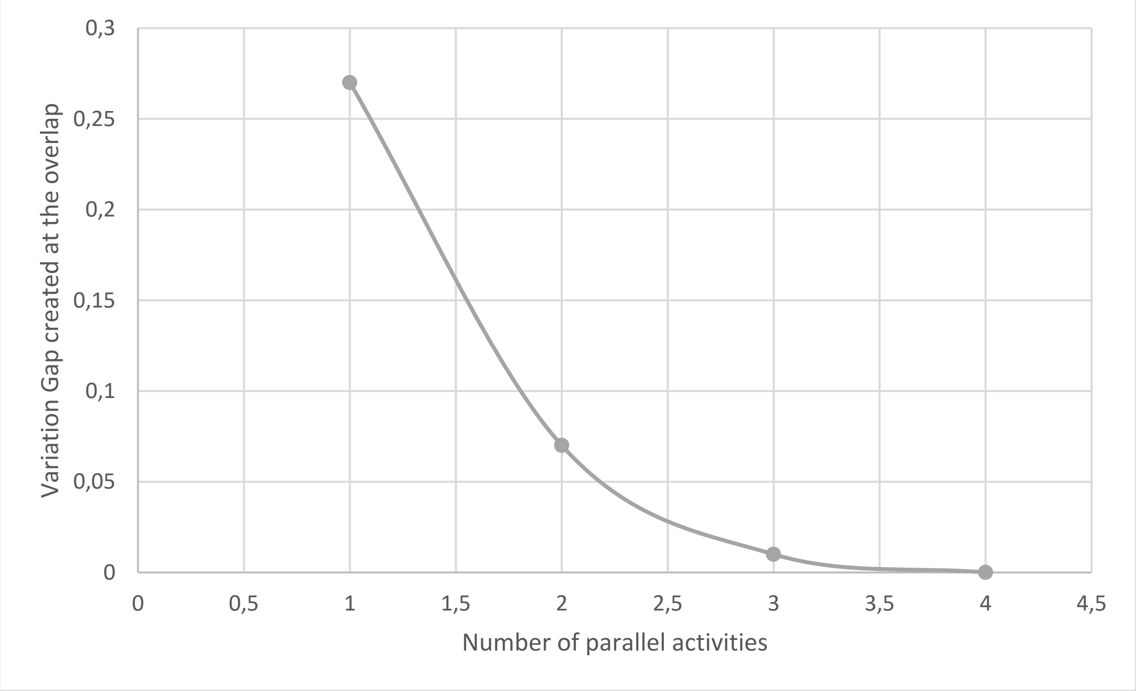

***Fig.4:** Variation Gap at the overlap between the parallel activities and the subsequent activities as the number of parallel activities increases.*

When looking at the Variation Gap in the entire sequence, it can be noticed that the size of the Gap depends on the Variation Gap caused by the activities taking place before the parallel activities, as shown in Fig. 5. This is because that gap is transferred to all subsequent parallel activities. Thus, the difference in the size of the Variation Gap emerges when the Variation Gap created by the subsequent activities is different from the Variation Gap absorbed when the number of parallel activities are increased. The simulation shows the following:

- If the Variation Gap at the activities before the parallel activities is above sequence average, the Variation Gap increases as the number of parallel activities is increased.
- If the Variation Gap at the activities before the parallel activities is at sequence average, the Variation Gap is unchanged irrespective of the number of parallel activities.

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- If the Variation Gap at the activities before the parallel activities is below sequence average, the Variation Gap decreases as the number of parallel activities is increased.

In further calculations the Variation Gap at the activity before the parallel activities is set to the average value; thus, the only reduction in variation is created in the overlap shown in Fig. 4.

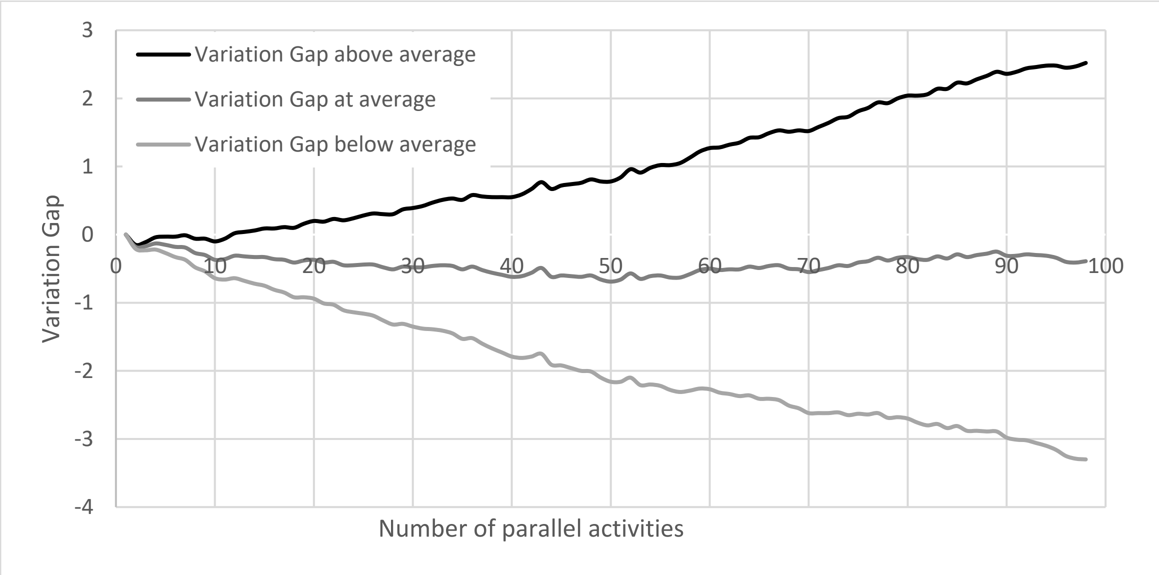

Fig.5: *The increase in Variation Gap is dependent on the Variation Gab created by the previous activities.*

When parallel activities are used in the schedule, a new type of gaps emerges. The gaps are caused by interdependencies in the network. The gaps emerge when an activity depends on the completion of more than one previous activity and one of these is completed before the others. These gaps are defined as Network Gaps and are often referred to as merge bias.

Network Gaps only emerge in the overlap between the parallel activities and the subsequent sequence. When increasing the number of parallel activities, the size of the gap increases because the likelihood of extremes increases. Simulation results show a logarithmic relationship between the size of the Network Gap and the number of parallel activities, where the increase in gap declines with increase in number of parallel activities as shown in Fig. 6. The decline can be explained by the fact that the Network Gap per activity increases only when more extreme variation occurs between parallel activities.

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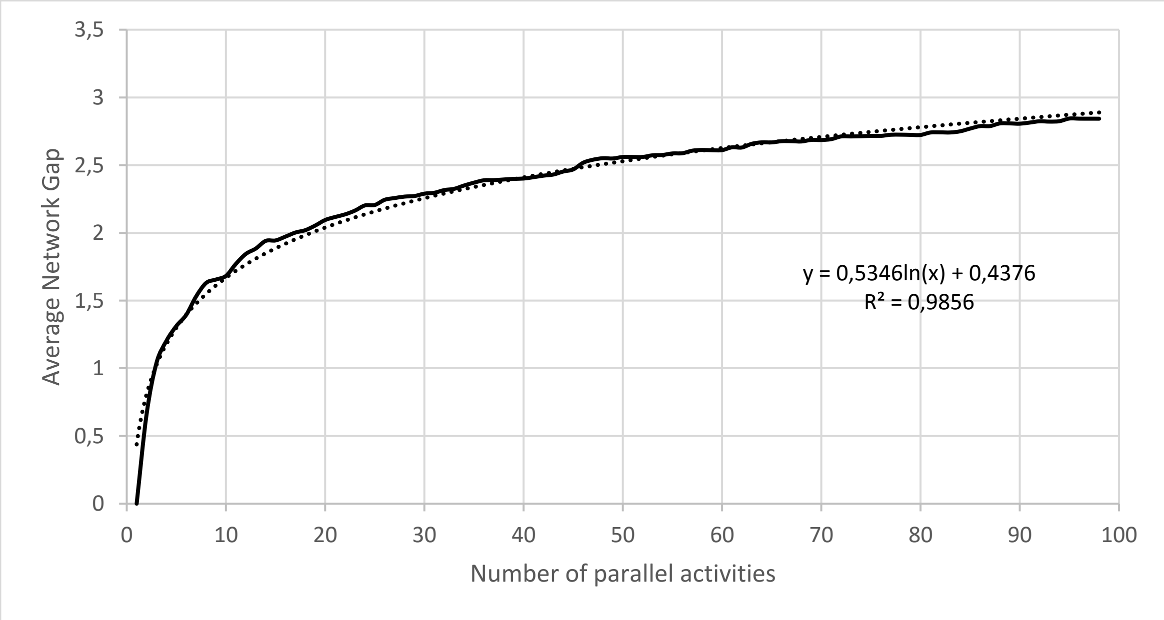

Fig. 6. Average wasted time per activity caused by Network Gaps.

The total Network Gap increases steadily as the number of parallel activities increase as Fig. 7 shows. Simulation results reveal that there is a linear relationship between the number of parallel activities and the size of the Network Gap. The increase emerges because the Network Gap is added to all parallel activities completed before the activity with the longest duration. The small bend at the beginning of the graph is caused by the increase of difference between the fastest and slowest completed activity.

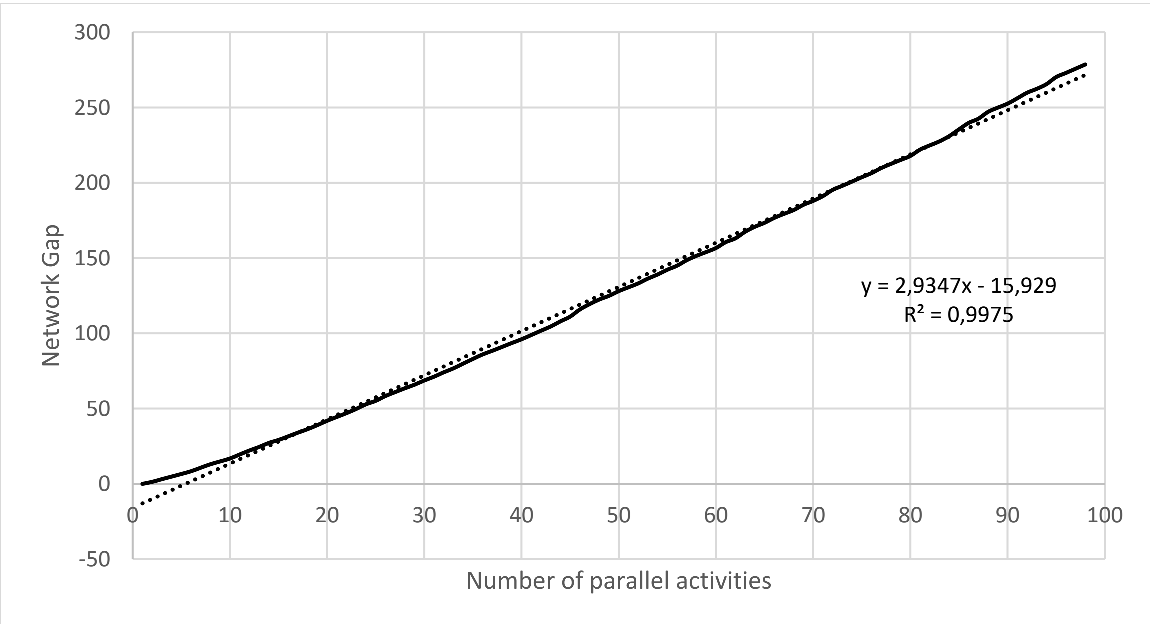

Fig.7: The wasted time caused by Network Gaps as the number of parallel activities increases.

When comparing the size of the Variation Gap with the size of the Network Gap, the negative effects of the increase in the Network Gap easily exceeds the positive effects of a possible reduction in the Variation Gap.

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Thus, by increasing the number of parallel activities, the size of the gaps in the production work flow increases.

Waiting days

Delayed activities cause an increase in waiting time to the subsequent activities. Hence, while the Network Gap creates waste in the parallel activities, waiting time creates waste to the subsequent activity. In the simulation exercise, the waiting time is measured in waiting days where two measures of waiting days are calculated. Waiting days$_{nup}$ corresponds to the situation where the initial schedule is kept through the entire construction process. Waiting days$_{up}$ corresponds to the situation where the schedule is continuously updated to reflect the current progress. In this case, a delayed activity is only causing waiting time to the subsequent activity then the site-manger spots the delay, intervenes and adjusts the schedule so the upcoming activities stays unaffected by the delay. Simulation results are shown in Fig. 8.

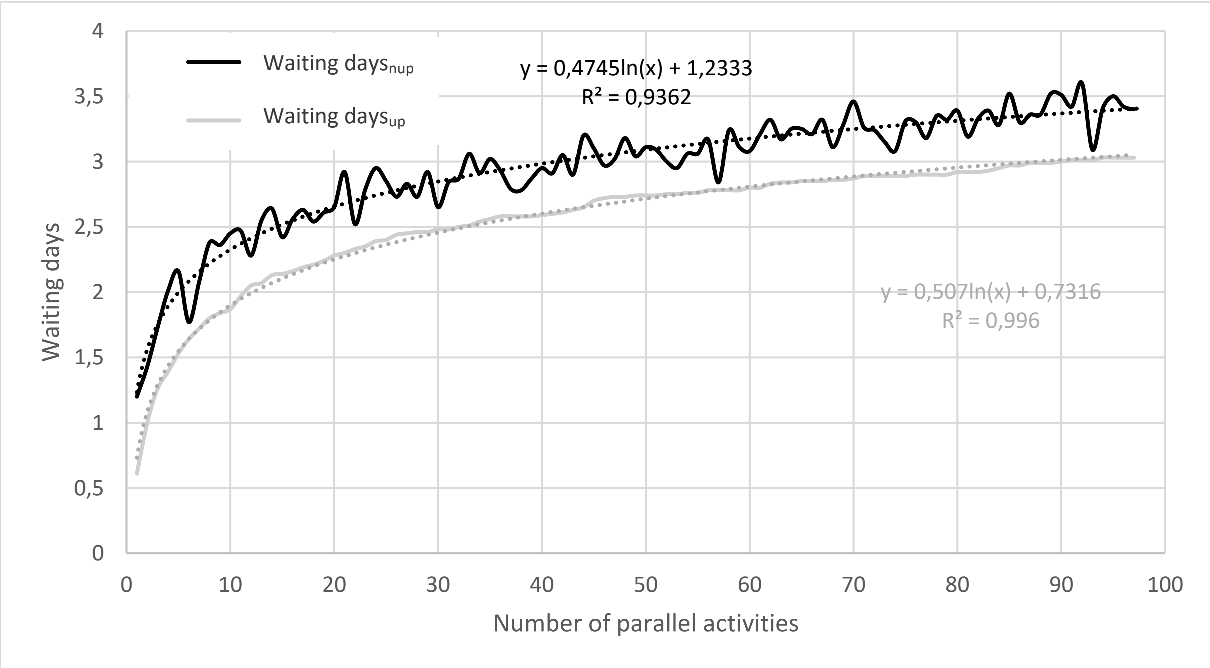

Fig.8: *Waiting days$_{up}$ and Waiting days$_{nup}$ emerging between the parallel activities and the subsequent activity.*

An increase in parallel activities increases the risk of waiting time in the subsequent activity, as shown in Fig. 8. The increased risk is caused by an increased likelihood of delayed activities and hence an increased waiting time for the subsequent activity. The increase in waiting time is declining because of a decrease in in the occurrence of extreme variations.

The increase in waiting time is reduced when looking at the entire production work flow, see Fig. 9 where the results are summarized. First of all, the number of waiting days are dependent on the waiting time caused by the activity preceding the parallel activities. If the waiting time caused by the previous activity is below average the number of waiting days are decreasing; conversely the waiting times are increasing if the waiting time is above average. Both the increase and decrease will be linear and directly dependent on the number of parallel activities. This effect is identical for Waiting days$_{up}$ and Waiting Days$_{nup}$.

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Moreover, when the waiting time caused by the previous activity is at average, an increase in Waiting Days$_{up}$ from 60.05 to 62.09 is observed, as shown in Fig. 9. Where most of the increase is occurring between 1 and 10 parallel activities. On the other hand, the Waiting Days$_{nup}$ is decreasing from 2137.56 to 101.24 days, as Fig. 10 shows. Thus, the number of waiting days when keeping the schedule constant will be higher than when continuously updating the schedule. The difference will be highest when completing the activities in a linear sequence while the difference will be minimal when completing the activities in parallel. The reason why Waiting Days$_{nup}$ is much larger than Waiting Days$_{up}$, is because the waiting time is transferred to the subsequent activities while the waiting time is reset when the schedule is updated.

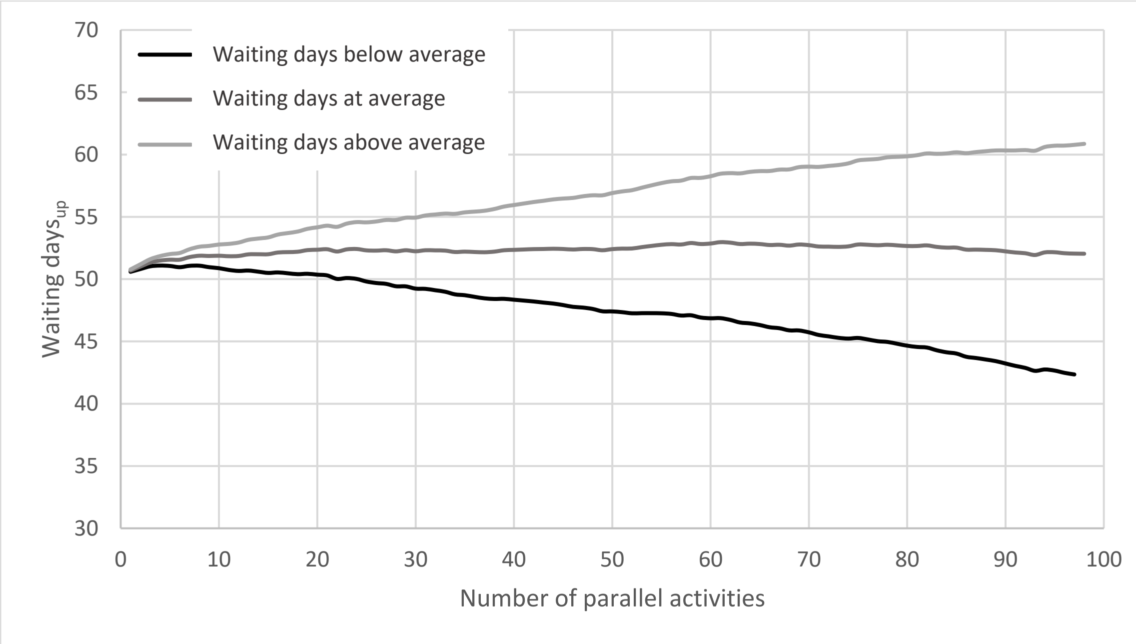

Fig. 9: *The increase in Waiting days$_{up}$ is dependent on the number waiting days created by the previous activities.*

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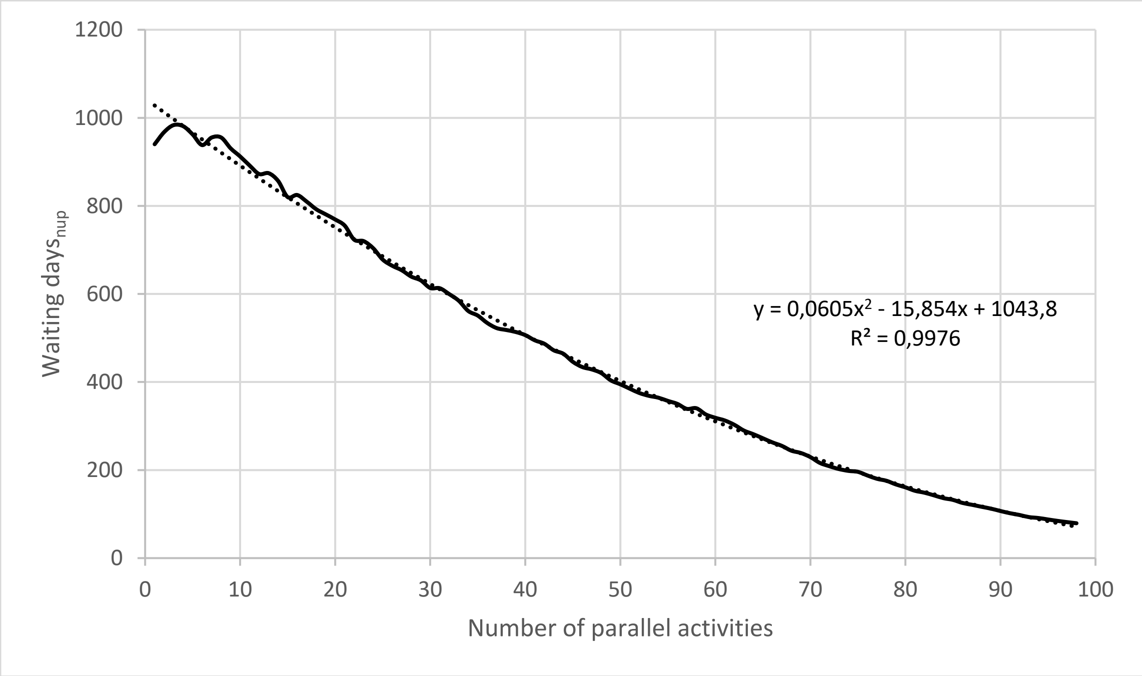

Fig. 10: *The number of waiting days$_{nup}$ in relation the number of parallel activities.*

Delay

Delay is undesirable in a production system. Two different measurements of delay are calculated Delay$_{nup}$ and Delay$_{up}$. Delay$_{nup}$ includes delays resulting from both positive and negative variation, but positive variation cannot bring the production ahead of schedule because the following activity starts on schedule, resulting in a wasted positive variation. Delay$_{nup}$ corresponds to keeping the initial schedule and not updating the schedule through the entire construction process. On the other hand, Delay$_{up}$ includes only negative variation as it corresponds to a situation where the schedule is continuously updated; thus, the start time of the following activity is continuously adjusted and results in wasting all of the positive variation.

Simulation results show that the activity that follows the group of parallel activities experiences an increased amount of delay as shown in Fig. 11. The increase in delay is a result of the increased likelihood of delay amongst the parallel activities as the start of the subsequent activity is affected by the finish of the longest activity among the group. The effect follows a logarithmic curve and is strongest for Delay$_{up}$ and weakest for Delay$_{nup}$.

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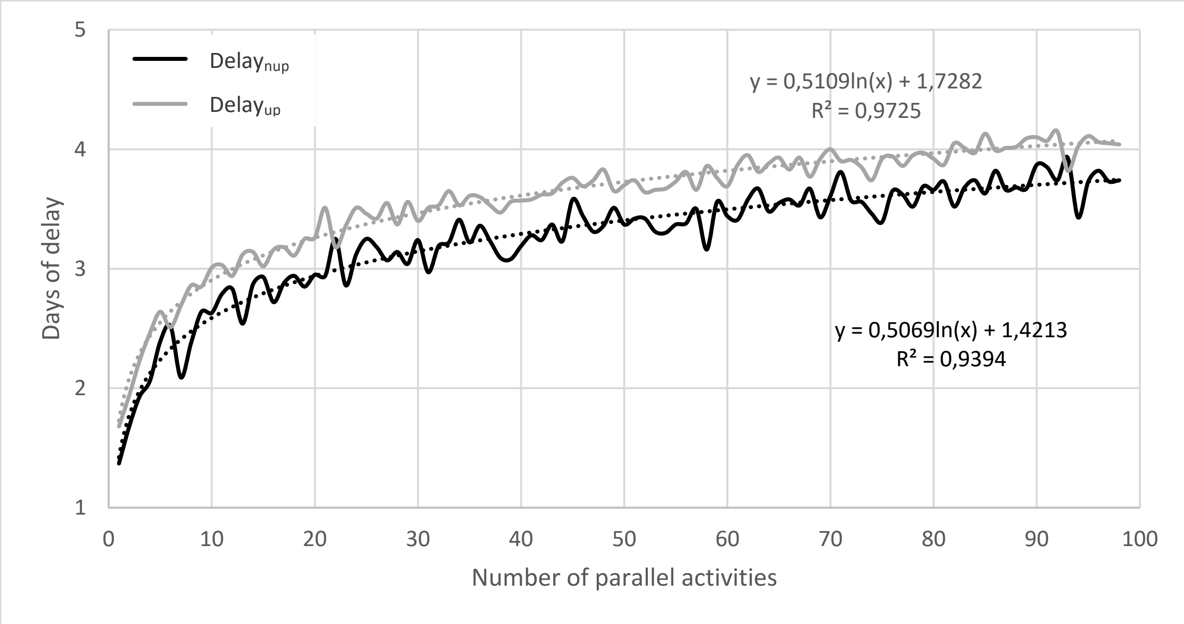

Fig.11: *The increase in delay in the activity following the parallel activities caused by increasing the number of parallel activities.*

Simulation results show a linear relationship between delay and the number of parallel activities. The total effect on delay is positive as shown in Fig. 12. Reduced delay, reduces the time needed for production. $Delay_{up}$ is larger than $Delay_{nup}$ when the number of linear tasks is large. But as the number of parallel tasks increases the difference between the two delay times decreases.

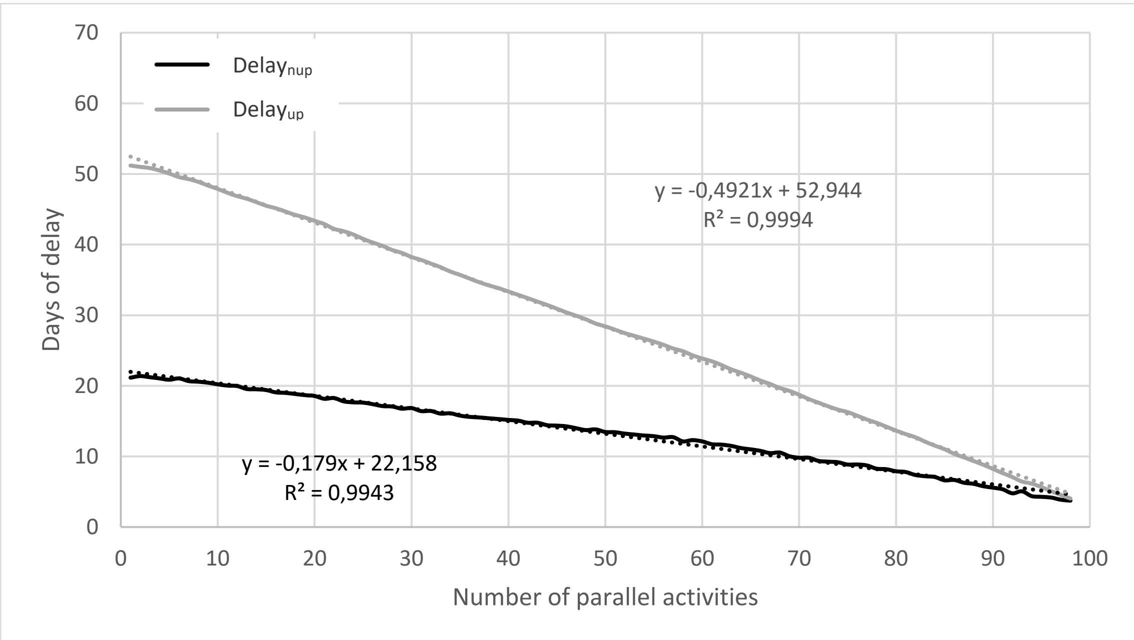

Fig. 12: *The decrease in the total delay caused by increasing the number of parallel activities.*

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Effect of parallel activities

One major reason for using parallel activities is that it reduces production time; the reduced production time is shown in Fig. 13.

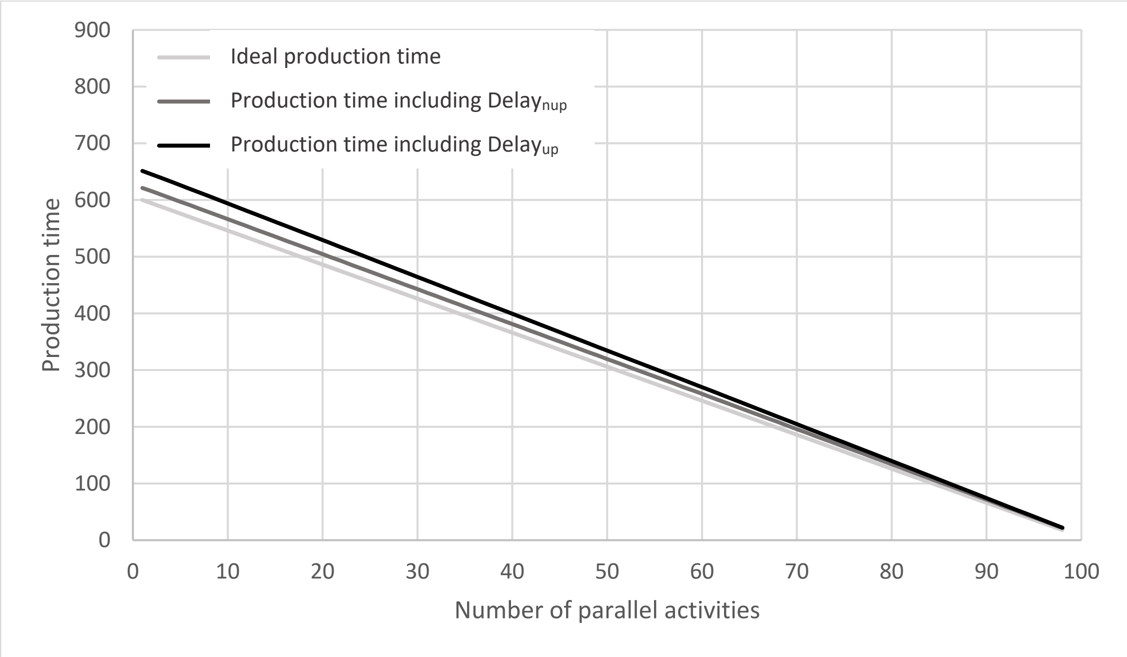

Fig. 13: *Decrease in project duration as the number of parallel activities increase.*

Using parallel activities also affects the amount of waste. The sum of waste is calculated by adding waiting days, variation gaps, network gaps as shown in the equation 1:

$$\sum WASTE = Waiting\ Days + Variation\ Gaps + Network\ Gaps \qquad \text{(Equation 1)}$$

Waiting days are direct waste, where work crews are waiting because the previous activity is not yet completed. Variation gaps and Network Gaps are wasted opportunities for production. The effect of the total waste is a prolonged construction period and increased project cost. The importance of minimizing waste is illustrated by Thomas et al.'s (1990) activity model. Thomas et al. (1990) studied productivity in on-site production and found that waiting time and wasted opportunities accounts for almost a third of the total working hours.

The total waste in work days, is shown in Fig. 14. The wasted production capacity can be calculated by multiplying with the average productivity and is thus 1.88 times higher.

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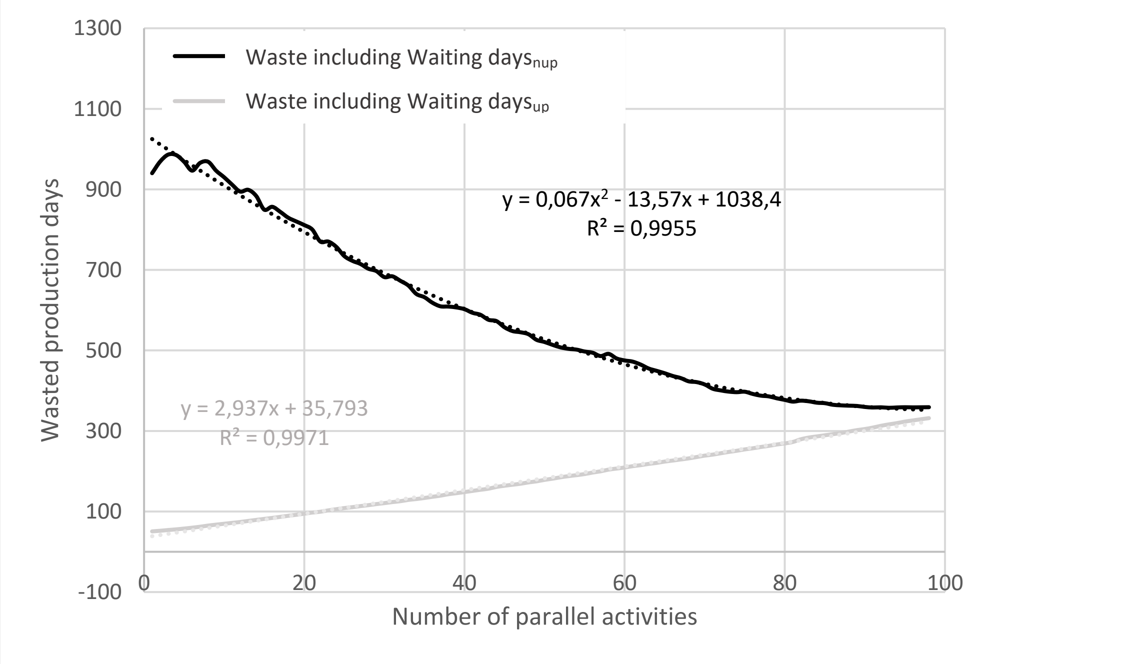

Fig. 14: The amount of wasted production days in relation to the number of parallel activities.

The effect of using parallel activities is very dependent on how the schedule is updated. If the schedule is not updated, the total waste goes down as the number of parallel activities increases. On the contrary, if the schedule is constantly updated to reflect current progress, the total waste will increase as the number of parallel activities increases. In general, due to waiting time transferred from previous activities more waste is created if the schedule is not updated. Thus, updating the schedule makes the production more robust against variation.

Implications of the findings

Using parallel activities have a positive effect on production time and delay, while its effect on waste such as production gaps and waiting delays depends on how often the schedule is updated. In general, the increase in parallel activities has a negative effect on production gaps.

As a matter of fact, keeping the initial schedule throughout the entire construction process with no updates usually does not occur. On the other extreme contrary, the schedule is rarely updated after each activity. If the schedule is updated weekly or monthly, the actual waste will follow a line that lies between the two extremes: Waste$_{up}$ and Waste$_{nup}$. Based on the simulation results, it can be concluded that when the schedule is updated more frequently, less waste is produced. Moreover, since waste happens between handovers, it can be concluded that the smaller durations of activities the more often needs the schedule to be updated.

Also, when the number of parallel activities increase, more gaps emerge in the production workflow. This makes it even more important that the site-management is responding and acting to the best of their ability to exploit the gaps. Managers can respond either:

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1) By reducing variation and hindering it in from reaching the production, for instance by ensuring that the activities are ready for completion. 2) By removing the effects of variation by the means of buffers and flexibility to absorb both positive and negative variation.

Due to the complexity of planning, sense and response of planners to the current situation are required (Snowden 2002). Moreover, a planner needs to have a constant awareness towards the schedule and the progress to sense, analyze and foresee if an activity is finished to early or too late and to respond by having the next crew ready exactly in time for the handover.

The focus has in the simulation been on the task sequence and on task transformations. The simulation is based on the assumption that all resources are available and that it is possible to perform the planned activities. Because the simulation is mainly focused on the transformations where the flow of pre-requisites and resources are considered as given, the findings only reveals the waste create during the transformations. This includes production gaps and waiting time caused by previous activities not being completed. If the resources have been considered other types of waste would have been revealed, such as stockade of and dwindling materials, idle machines, or activities not being able to start because resources are not available.

Increased complexity and variation increases waste related to both transformations and resources, because it will be more difficult to predict the needed resources and the production progress. Because, a larger number of parallel activities will lead to a more complex construction process, the threat of waste created from resource inability etc. will increase.

Using parallel activities compresses the schedule to accelerate work. When kept under control work acceleration can be used as a managerial-tool to make up for lost time, but only to a certain limit. When the production reaches a saturation-point work spaces and resources will be shared and storage will be limited (Ahmad, An 2008; Bertelsen 2003) which increases complexity (Salem, Solomon et al. 2006). Increased complexity will lead to increased variation, and thus, increased gaps, waiting days, and delay. Accelerating work by overstaffing will have a negative impact on both cost and productivity (Noyce, Hanna 1998).

The saturation point, together with the negative effect of overstaffing, are very difficult to estimate. Both are project specific and dependent on multiple factors. In a case study conducted by Thomas (2000), the effects of accelerating the work were examined; the findings revealed a substantial productivity loss at 25 %. If the negative effects associated with overstaffing has been taken into consideration in the simulation, more waste and delay will be introduced into the production systems as the number of parallel activities is increased. In conclusion; the use of parallel activities will, as a rule of thumb, increase waste in the production, caused by an increased amount of production gaps. This has to be taken into account by project managers and planners when planning and scheduling the production work on a project.

Conclusion and further research

The ideal approach in improving the production flow in construction is to eliminate variation in the production output. Therefore, variation has been a focus area of several research studies, but due to the complex nature of construction it has proven difficult to reduce and impossible to eliminate.

Variation that slips through the shield that protects production needs to be handled. Traditionally focus has been on handling the effects, by adjusting crew sizes, work hours, or by applying buffers. This study has investigated a third option and contributes to create an understanding to how the production sequence can be rearranged to render production more robust towards variation. This points the attention to the potential in

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exploiting the positive variation and the emerging gaps in the production. The more the number of parallel activities, the more complex is the activity sequence and thus the more important it is to exploit the positive variation to minimize gaps, waiting days, and delay.

The findings show that the effects of variation depends on how the schedule is updated, where more waste is created the more infrequent the schedule is updated. In the simulated activity configuration, if more parallel activities are applied, the number of waiting days will decrease together with the production time; however, more gaps will emerge in production. The balance between the negative and positive effects of this increase in parallel tasks depends on how often the schedule is updated. If the schedule is updated regularly, parallel activities will have a negative impact on waste. Thus this research shows that, keeping the sequence as simple as possible and reducing the number of parallel activities will increase schedule robustness and decrease the number of production gaps created by variation. Still, the sequence need to be adjusted in relation to the construction projects given timeframe. Thus, a sequence where all activities are placed on a single line is never be applicable. But the production manager needs to weigh the effects of increasing the number of parallel tasks against the increase in production gaps.

Parallel activities are often used as an instrument to compress the schedule, this because parallel activities reduces production time. Schedule compression are used either by the owner, in an attempt to finish on schedule or by the contractor to make up for lost time. This study revealed that by compressing the schedule variation will increase waste. The more the schedule is compressed the more waste emerges.

A production manager needs to both reduce variation and reduce the negative impacts of variation if it occurs. To reduce the negative impacts of variation the production manager needs to make the sequence robust to variation. Simultaneously, the production manager needs to handle the variation which slips through to ensure that the effects of positive variation as well as negative variation is managed.

In future research different sequence patterns will be examined to make the schedule more robust against variation. More adjustments will be built into the simulation, for instance allowing changes in task duration.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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